

Deeply Virtual Compton Scattering at HERA

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Deeply virtual Compton scattering has recently been studied by three HERA experiments, H1, ZEUS and HERMES, covering a broad range of kinematic regimes. We present cross section measurements of the two collider experiments in the kinematic region $2 < Q^2 < 100 \text{ GeV}^2$ and $30 < W < 140 \text{ GeV}$, and compare them to QCD-based calculations. HERMES measurements of azimuthal asymmetries and their kinematical dependences are presented for $Q^2 > 1 \text{ GeV}^2$ and $2 < W < 7 \text{ GeV}$.

1. Introduction

The internal structure of the nucleon has long been studied with inclusive deep-inelastic lepton scattering. From these studies, the spin-dependent and spin-independent nucleon structure functions and corresponding parton distribution functions have been extracted. Recently, the formalism of generalized parton distributions (GPD) [1]-[3] was introduced. In this framework, non-forward degrees of freedom are probed in exclusive processes such as meson production or deeply virtual Compton scattering (DVCS), the electroproduction of a single real photon on the nucleon, which has been studied at DESY [4]-[6] and Jefferson Lab [7]. This opens the way to access the distribution of partons in the nucleon perpendicular to its momentum [8], and to access the contribution of the orbital angular momenta of the quarks to the nucleon spin [9].

2. DVCS at HERA

2.1. DVCS at H1 and ZEUS

The HERA storage ring at DESY provides an 820-920 GeV proton beam and a 27.6 GeV electron or positron beam to the two collider experiments, H1 and ZEUS. At collider energies, the leading order handbag diagram (Fig. 1 a) is accompanied by a sizable contribution of colour singlet two-gluon exchange (Fig. 1 b). In both cases, the final state is indistinguishable from that of the Bethe-Heitler (BH) process, in which the real photon is radiated off the lepton. The BH process constitutes a background to the DVCS pro-

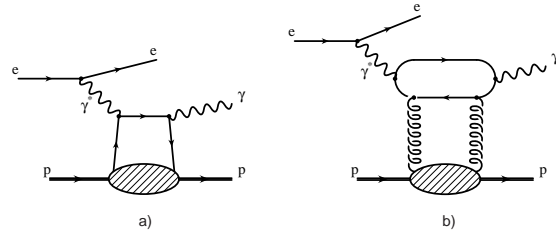


Figure 1. a) leading order handbag diagram, b) NLO colour singlet two-gluon exchange.

cess. Since it is purely electromagnetic, its amplitude can be calculated exactly. This contribution is subtracted from the combined DVCS+BH data by means of a Monte Carlo simulation that is cross checked with a BH-dominated sample of the experimental data [4,5].

The cross section from the H1 experiment, shown in Figs. 2 and 3, was measured in the 1997 running period with an 820 GeV proton energy. The sample corresponds to an integrated luminosity of 8 pb^{-1} . The data cover a kinematic range in four-momentum transfer squared Q^2 from 2 to 20 GeV^2 , invariant mass of the photon-nucleon system W from 30 to 120 GeV and the square of the momentum transfer to the proton $|t| < 1 \text{ GeV}^2$, over which the cross section is integrated. The data in Figs. 2 and 3 have been scaled to central values of $W=75 \text{ GeV}$ and $Q^2=4.5 \text{ GeV}^2$, respectively. Here, also theoretical predictions for DVCS at H1 kinematics from a GPD-based model (FFS, [10]), as well as from a colour dipole model (DD, [11]), are shown. In both models, the expo-

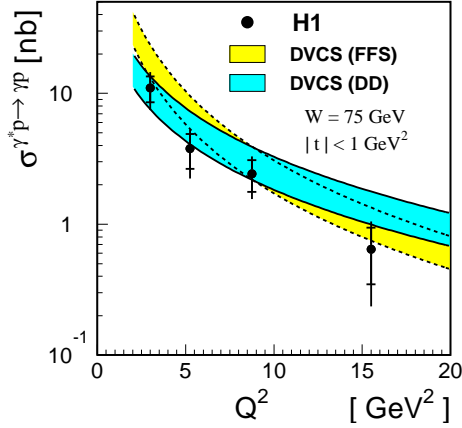


Figure 2. Q^2 dependence of DVCS cross section for the H1 data [4], GPD predictions (light shade) [10], a colour dipole model (dark shade) [11].

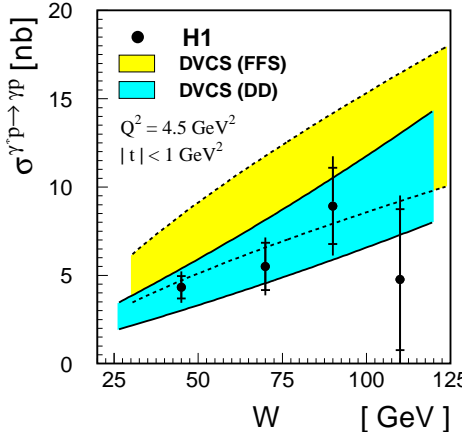


Figure 3. W dependence of DVCS cross section for the 1997 H1 data [4], overlays as in Fig. 2.

nential t -dependence factorizes from the Q^2 and W dependences. Since the t -dependence of the cross section was not measured, upper and lower bounds are determined by taking values of the t -slope parameter b of 5 and 9 GeV^{-2} . A newer GPD-based approach can be found in [12].

The ZEUS results are based on data taken between 1996 and 2000, and, for the first time, also make use of the HERA electron beam. The integrated luminosities are 95 pb^{-1} for e^+p and 17 pb^{-1} for e^-p collisions. The data were analyzed in the kinematical region defined by

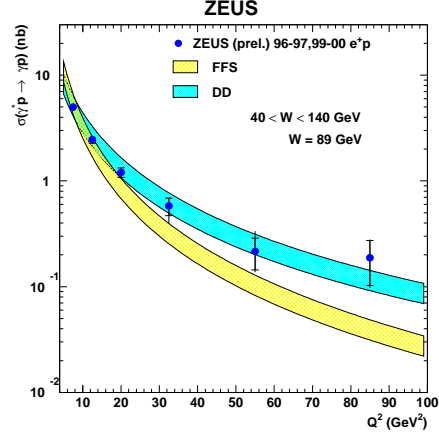


Figure 4. Q^2 dependence of DVCS cross section for the ZEUS positron data, overlays as in Fig. 2.

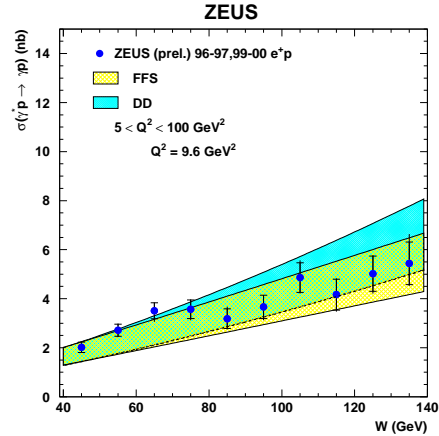


Figure 5. W dependence of DVCS cross section for the ZEUS positron data, overlays as in Fig. 2.

$5 < Q^2 < 100 \text{ GeV}^2$ and $40 < W < 140 \text{ GeV}$, with no cut on t . The data were found to agree for both lepton charges. The e^+p data shown in Figs. 4 and 5 are scaled to central values of $W = 89 \text{ GeV}$ and $Q^2 = 9.6 \text{ GeV}^2$, respectively. The data are overlaid with theoretical predictions from the same models as the H1 data. Due to the larger kinematical range and integrated luminosity, the ZEUS data have enough leverage and statistical accuracy to discriminate between different theoretical predictions and can be used to constrain the predicted Q^2 dependence of theoretical models. Here, the ZEUS data are seen to favour the

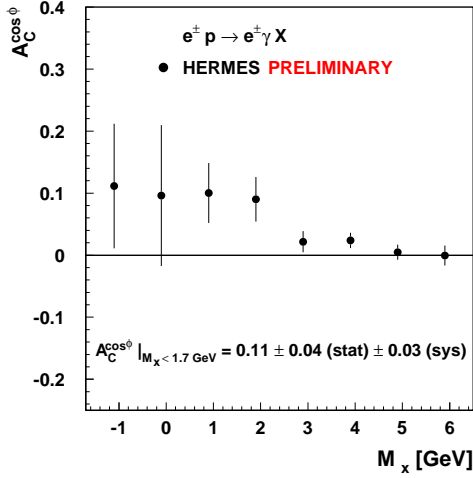


Figure 6. The $\cos \phi$ moment of the beam charge asymmetry from HERMES data from 1998 and 2000.

less steep slope in Q^2 of the colour dipole model. The W -dependence of the data is described well in both cases, reflecting the steep rise in gluon density at lower x_B , the momentum fraction of the struck parton in the nucleon.

The ZEUS and H1 data cannot be compared directly due to the different kinematic ranges. However, if the observed functional behaviour in Q^2 is used to scale the H1 data to the ZEUS central kinematics, the two data sets agree.

2.2. DVCS at HERMES

The fixed target experiment HERMES makes use of the 27.6 GeV polarized HERA positron beam incident on a storage cell that is filled with unpolarized gas (hydrogen, deuterium, or heavier nuclei). At HERMES kinematics, the BH amplitude largely dominates the DVCS amplitude. However, the DVCS and BH amplitudes interfere, giving rise to a single-spin asymmetry, which depends on beam charge, helicity, and the azimuthal angle ϕ between the lepton scattering plane and the reaction plane of the real photon and recoil proton. By extracting the $\sin \phi$ and $\cos \phi$ moments of the exclusive data, access is obtained to certain combinations of DVCS amplitudes [13].

The $\sin \phi$ moment of the beam spin asymmetry

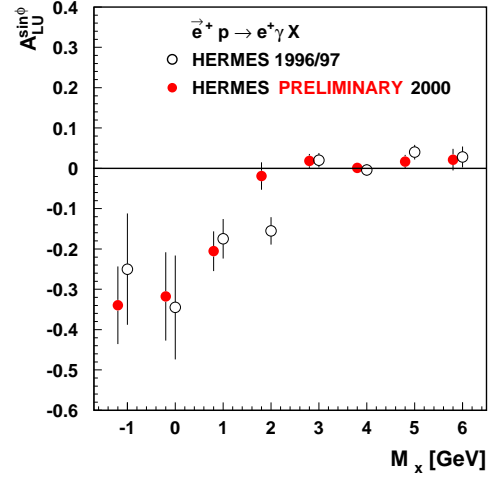


Figure 7. The $\sin \phi$ moment of the beam spin asymmetry from HERMES data from 1996/1997 (empty symbols) [6] and 2000 (filled symbols).

is calculated as

$$A_{LU}^{\sin \phi} = \frac{2}{N} \sum_{i=1}^N \frac{\sin \phi_i}{(P_l)_i},$$

where P_l is the beam polarization for each event. The $\cos \phi$ moment is determined similarly from the beam charge asymmetry with an unpolarized beam.

The HERMES forward spectrometer detects the scattered lepton and the real photon, but not the recoiling proton. Therefore the exclusivity of an event is measured through the missing mass (M_x) of the event, which in the exclusive case is equal to the proton mass. Examples are shown in Figs. 6 and 7, in which the $\cos \phi$ moment of the beam charge asymmetry for the 1998 and 2000 data, and the $\sin \phi$ moment of the beam spin asymmetry for the 1996/1997 data [6] and the 2000 data are shown. Asymmetries are observed at values of $M_x < 1.2 \text{ GeV}$, in the exclusive region. At higher missing masses, where non-exclusive processes dominate, asymmetries vanish. The two regions overlap slightly, because the resolution in M_x is limited by the energy resolution of the electromagnetic calorimeter. The $\sin \phi$ measurements were confirmed at Jefferson

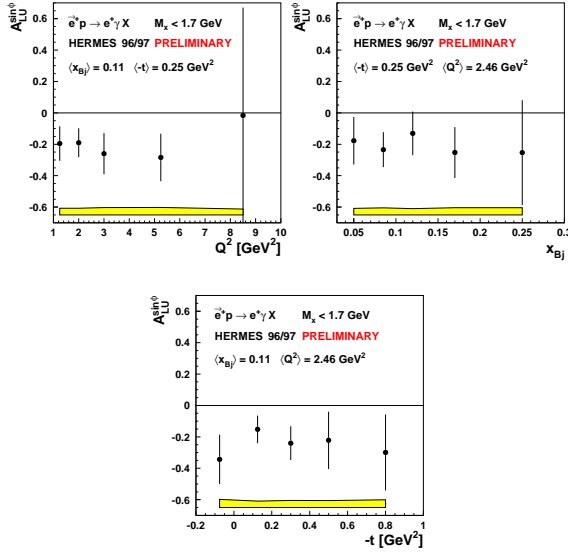


Figure 8. The Q^2 , x_B and t -dependences of the $\sin \phi$ moment of the beam spin asymmetry from HERMES data from 1996 and 1997.

Lab [7]. GPD-based predictions can be found in Refs. [12,13].

From the exclusive sample ($M_x < 1.7$ GeV) of the 1996/97 data the kinematic dependences of the beam spin asymmetry were extracted as functions of Q^2 , x_B and t (preliminary results shown in Fig. 8). In the case of t , as with M_x , the reconstruction relies on the photon energy measured in an electromagnetic calorimeter. Therefore some events are reconstructed at $-t < 0$.

3. Outlook

The HERA run II starting in 2002 will be used by all three experiments to improve the DVCS measurements. In the 2001 shutdown, spin rotators were installed before and after the collider experiments H1 and ZEUS, thus allowing for spin-dependent measurements. It is planned to run alternately with electron and positron beams.

The H1 experiment will install a Very Forward Proton Spectrometer in 2003 [14], allowing it to measure $|t|$ at small values of W . In addition, the precise tracking data from the Backward Silicon Tracker will be used for a measurement of azimuthal asymmetries. The measurement of

differences in the cross section for the available beam polarizations and charges will be the main goal of the ZEUS DVCS analysis. The HERMES experiment will improve the exclusivity of its DVCS sample, as well as the t -resolution, by installing a large acceptance recoil detector around the HERMES target [15].

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